MILLIMETER-WAVE RECEIVER COMPONENTS

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ABSTRACT

This paper presents an overview of the state-of-the-art performance of mm-wave receiver front-end components. Topics covered include filters, diplexers, mixers (broadband and narrowband) and local oscillators (free-running and phase-locked). Examples of mm-wave receiver front-end configurations are given and performance tradeoffs are discussed.

1.0 INTRODUCTION

Much of the impetus behind the successful development of mm-wave radar, communications and EW systems is due to the availability of small, rugged receivers with outstanding performance characteristics. The receiver designer today can optimize system tradeoffs by selecting the component technology best fit to meet the system performance requirements. Four types of components will be discussed in this paper: filters, frequency diplexers, balanced mixers and local oscillators.

Radar receivers are usually narrowband (IF bandwidth 500 MHz or less) and the main performance requirement is minimum noise figure. Some design tradeoffs are required for coherent and monopulse receivers, where requirements such as LO phase noise, frequency stability and channel-to-channel amplitude and phase tracking have to be met. EW receivers present a different problem; wherever signal frequency identification is needed, frequency accuracy and stability of local oscillators, instantaneous RF and IF bandwidth and intermodulation characteristics are important. Channelized receivers can be designed with channelized RF, channelized IF, or both. The general tradeoffs are:

1. Receivers with broader instantaneous RF and IF bandwidths (4 GHz or more) have higher receiver noise figure (partly due to higher mixer conversion loss and higher IF preamplifier noise figure) and degraded spurious performance (third order intermodulation and IF harmonics), but lower overall cost and volume, because of the need for fewer mm-wave mixers to cover a given band and the lower cost and complexity of IF diplexers.

2. Receivers with IF instantaneous bandwidths of 4 GHz or less have better noise figure and spurious performance, but if a large number of channels are needed to cover a given frequency band, the choice may be between RF diplexers and availability of space for several antennas (one antenna per channel), both of which result in increased cost and complexity.

   Hybrid designs incorporating some RF diplexing and some IF diplexing present the optimum tradeoff in most cases. The selection of optimum channel bandwidth is critically dependent on several parameters:

   a) RF diplexer loss and isolation versus bandwidth

   b) Mixer noise figure versus IF bandwidth

   c) Mixer intercept point

   d) IF preamplifier skirt selectivity

   e) LO frequency stability

   f) Mixer LO-to-RF isolation

   g) IF diplexer cross-over characteristics

A good knowledge of component performance characteristics is needed to select the optimum receiver design. In the remainder of this paper we present an overview of existing mm-wave receiver component technology and we indicate trends and directions for the future.

Receiver front-end components, specifically filters and mixers, is one area where transmission media other than metallic waveguide are likely to challenge the present dominance of metallic waveguide components, if not in electrical performance at least in cost and complexity. Indications are that suspended stripline, fin-line, dielectric waveguide and quasi-optical techniques are likely to offer selective advantages for specific frequency ranges and performance levels. Further development efforts are required to elucidate potential advantages and disadvantages. It is also very likely that hybrid components will emerge integrating several transmission media in different parts of the circuit, specially for mixers. We believe that it is premature to dismiss metallic waveguide or to adopt simplistic arguments favoring one or the other media, particularly when the range of frequencies and systems needs to be covered is as broad as it is, and continually expanding.

2.0 FILTERS AND DIPLEXERS

Waveguide filters and frequency diplexers have been designed and fabricated at frequencies up to 110 GHz. Three types of waveguide filters exist:

a) Low-pass filters, of the waffle-iron type, are limited to an upper frequency of 40 GHz due to limitations in fabrication techniques.

b) High-pass filters are based on waveguide cutoff properties. By careful design and fabrication of tapered transitions, insertion losses can be kept under 1 dB at 60 GHz and skirt selectivity is of the order of 30 dB at 200 MHz from band edge.

c) Bandpass filters are based on the classical iris-coupled cavity technique. Performance characteristics of a narrowband design at 94 GHz is given in Figure 1. The measured performance of two W-Band broadband filters is shown in Figure 2 (dashed line). Insertion losses of 0.6 dB for a seven section filter at Ka-Band can be achieved by using electroforming fabrication techniques. Typical losses for frequencies between 30 GHz and 100 GHz can be estimated by extrapolating between the values shown.

Waveguide diplexers consist of a Y junction with two filters properly spaced along the colinear arms. The out-of-band rejection is determined by the filters and the insertion loss is the sum of three components: filter loss, ohmic loss of the junction and mismatch loss. Contiguous-channel diplexers have relatively large mismatch loss at the crossover frequency, as shown in Figure 2 (solid line). A photograph of a W-Band diplexer is shown in Figure 3. Typical performance data for a Ka-Band non-contiguous diplexer is shown in Table I.

3.0 BALANCED MIXERS

Substantial development efforts in recent years involving both mixer diodes and circuits have resulted in the availability of new types of devices and the across-the-board improvement of critical mixer performance parameters, specially noise figure.

Three types of Schottky-barrier diodes are being used in mm-wave mixers: honeycomb, notchfront and beam-lead. Honeycomb diodes (Figure 4) are used with waveguide mixers and have the best noise figure performance potential, particularly above 100 GHz. The notch-front diode (Figure 5) is a variant of the honeycomb diode designed to fit the package requirements of suspended stripline circuit configuration. It has, however, one additional advantage in that it inherently reduces series resistance by reducing skin effect loss. Basically the notch-front diode is a honeycomb diode chip turned on its side.

Notch-front diodes offer significant advantages for operation above 100 GHz when used with subharmonically pumped mixers. They can also be used with fundamentally pumped mixers with suspended stripline IF output circuits.

Beam-lead diodes are whiskerless planar devices with a surface oriented configuration from which two beams extend for contact to an RF circuit (Figure 6). They are particularly well suited for fin-line, suspended stripline and dielectric waveguide circuits. Their performance capabilities below 100 GHz are comparable to that of honeycomb or notch-front diodes, whereas above 100 GHz the parasitic capacitance may result in higher noise figure.

TABLE I

Performance of a Ka-Band Non-Contiguous Diplexer

Channel 1 band-pass:	34.2 GHz to 35.4 GHz
Filter insertion loss:	<0.4 dB
Filter rejection:	>50 dB
Diplexer insertion loss:	0.8 dB
Diplexer rejection:	>50 dB
Channel 2 band-pass:	36.5 GHz to 38.6 GHz
Filter insertion loss:	<0.4 dB
Filter rejection:	>50 dB
Diplexer insertion loss:	<0.8 dB
Diplexer rejection:	>50 dB

Waveguide narrowband balanced mixers have been in operation at frequencies up to 140 GHz for several years. Figure 7 shows a 94 GHz mixer with 5.6 DSB NF (including an IF preamplifier with 10 MHz to 1010 MHz bandwidth and 3.5 dB NF), with a band-pass filter in the RF arm. Units similar to this one have been used in space programs and have been subjected to rigorous as well as environmental tests (e.g., 10000 g’s centrifugal acceleration on three axis for 30 seconds each).

Broadband balanced waveguide mixers can be implemented with the configuration shown in Figure 8. This particular unit was designed to be used with a scanning 50 GHz to 75 GHz local oscillator with 10 MHz to 500 MHz fixed IF bandwidth.

Other designs involving fin-line and dual-mode mixers are capable of achieving up to 20 GHz instantaneous IF bandwidth with a fixed local oscillator frequency. The performance of these mixers above 100 GHz is critically dependent on the cutoff frequency and circuit parasitics associated with beam-lead diodes.

Figure 9 shows a prototype subharmonically pumped mixer at 94 GHz (with a local oscillator frequency of 47 GHz). While capable of excellent noise figure performance at frequencies up to 180 GHz, the ultimate advantages of this design depend on the feasibility of developing practical fabrication and assembly techniques. The lack of suitable local oscillators operating above 110 GHz makes this design very attractive for operation in the 110 GHz to 200 GHz range.

Above 180 GHz, quasi-optical techniques offer the best promise. Figure 10 shows a quasi-optical 217 GHz single-ended mixer with an IMPATT local oscillator. A conversion loss of 10.6 dB was measured for this device.

Both dielectric waveguide and quasi-optical mixers are being designed to operate as subharmonically pumped mixers (i.e., with the local oscillator frequency equal to 1/2 or 1/4 the nominal frequency). Particular promise is shown by dielectric waveguide mixers in the 60 GHz to 200 GHz range for applications requiring large instantaneous IF bandwidth.

The third order intemodulation performance of a typical mm-wave balanced mixer/IF amplifier is shown in Figure 11. The 1 dB compression point is in the 0 dBm to +10 dBm IF output power range (with 25 dB RF-to-IF gain), and is primarily determined by the IF amplifier saturation characteristics. This is particularly relevant for broadband mixers with IF amplifiers in the 2-4 GHz or 4-8 GHz range.

4.0 LOCAL OSCILLATORS

The main requirement of mm-wave local oscillators is low AM noise. GaAs Gunn devices are used at frequencies up to 110 GHz and IMPATT oscillators (with suitable filters) can be used up to 220 GHz. The measured AM noise of a 94 GHz Gunn oscillator is shown in Figure 12. It should be noted that oscillators with higher AM noise can be used in conjunction with mixers with good LO noise suppression (35 dB or better).

Phase-locked local oscillators are used for both frequency accuracy (EW receivers) and low phase noise (coherent radar receivers). Figure 13 shows the measured FM noise of a 94 GHz phase-locked Gunn oscillator. The dashed line shows the theoretical minimum noise, as determined by the 100 MHz crystal reference oscillator, and the solid line shows the measured FM noise.

5.0 CONCLUSIONS

Sophisticated mm-wave receiver front-ends have been designed and fabricated with performance parameters not significantly different than those achievable at lower microwave frequencies. Further development efforts will result in improved bandwidth and noise figure performance through the use of novel circuit and diode techniques.

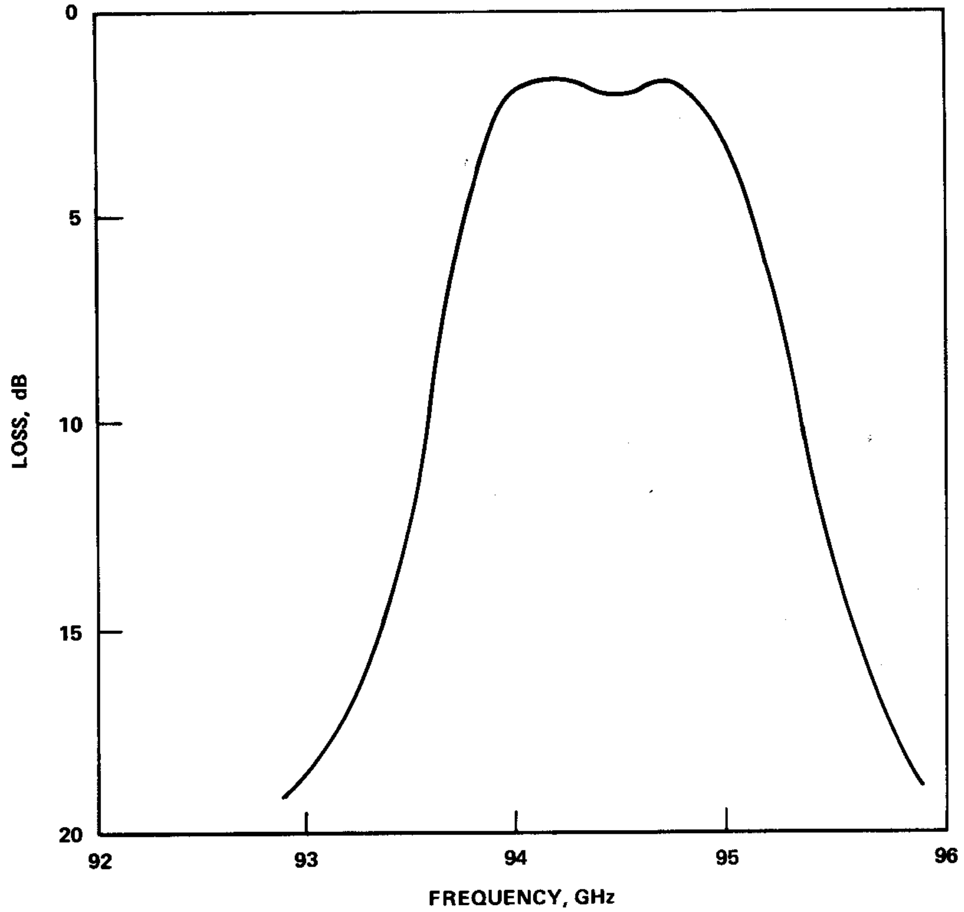

FIGURE 1 BAND-PASS FILTER PERFORMANCE AT 94 GHz.

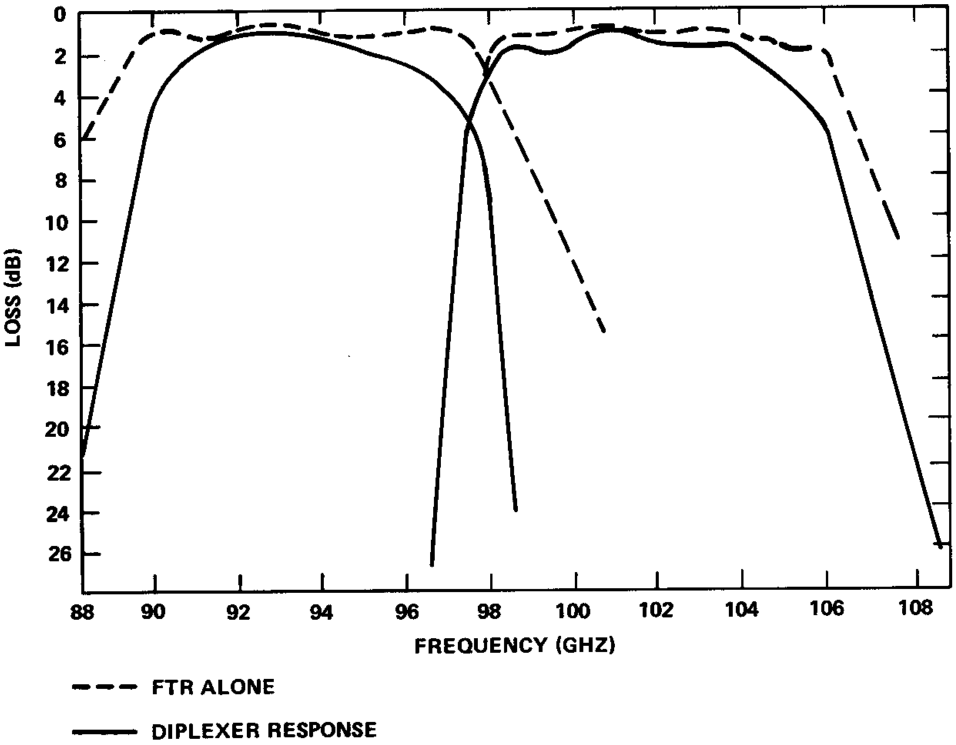

FIGURE 2 W-BAND BAND-PASS FILTER AND DIPLEXER PERFORMANCE.

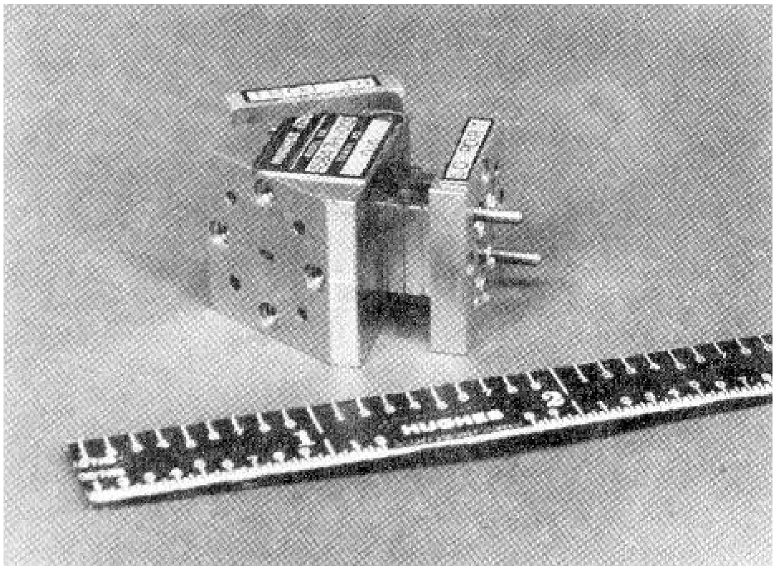

FIGURE 3 W-BAND DIPLEXER.

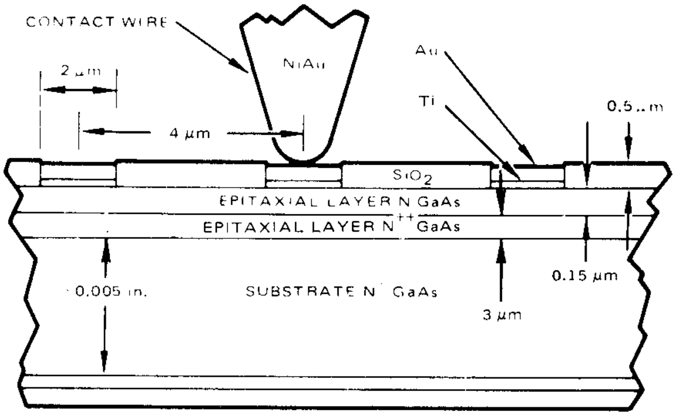

FIGURE 4A CROSS-SECTIONAL VIEW OF GaAs HONEYCOMB SCHOTTKY-BARRIER DIODE.

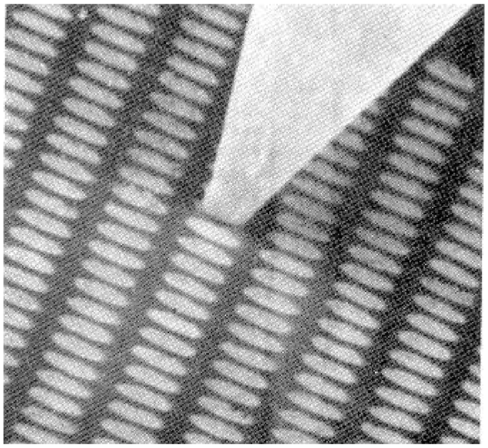

FIGURE 4B PHOTOGRAPH OF HONEYCOMB-WHISKER CONTACT.

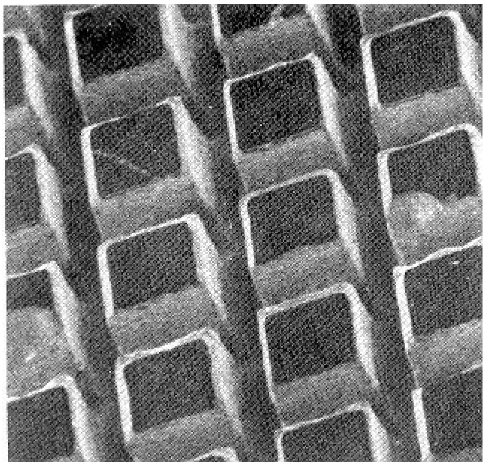

FIGURE 5 SEM PHOTOGRAPH OF NOTCH-FRONT DIODES.

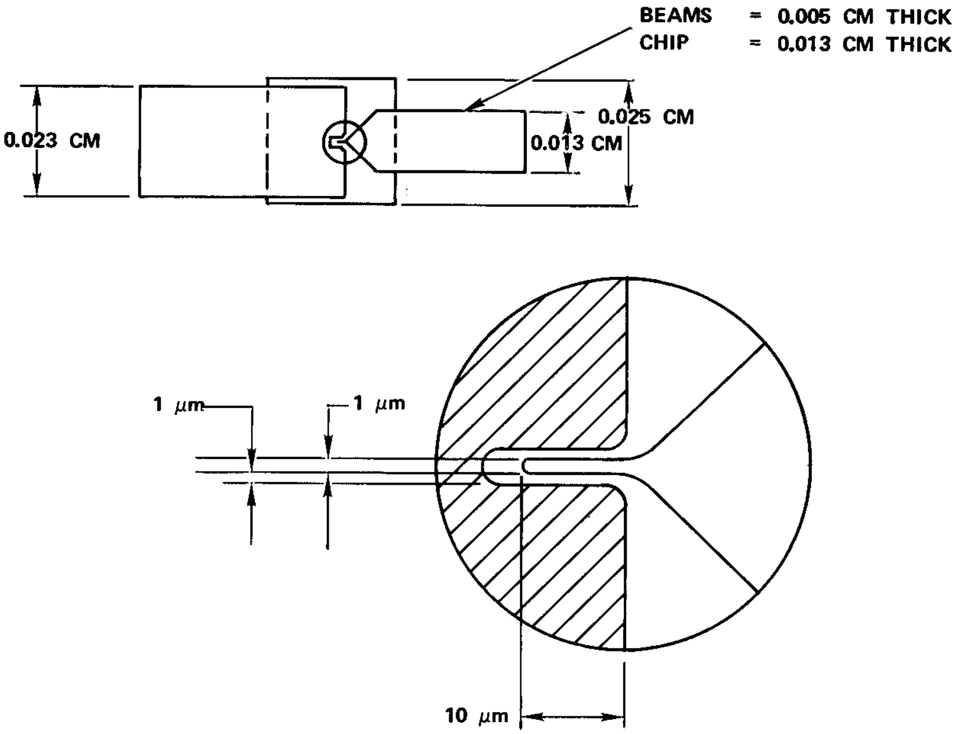

FIGURE 6A BEAM-LEAD MIXER DIODE.

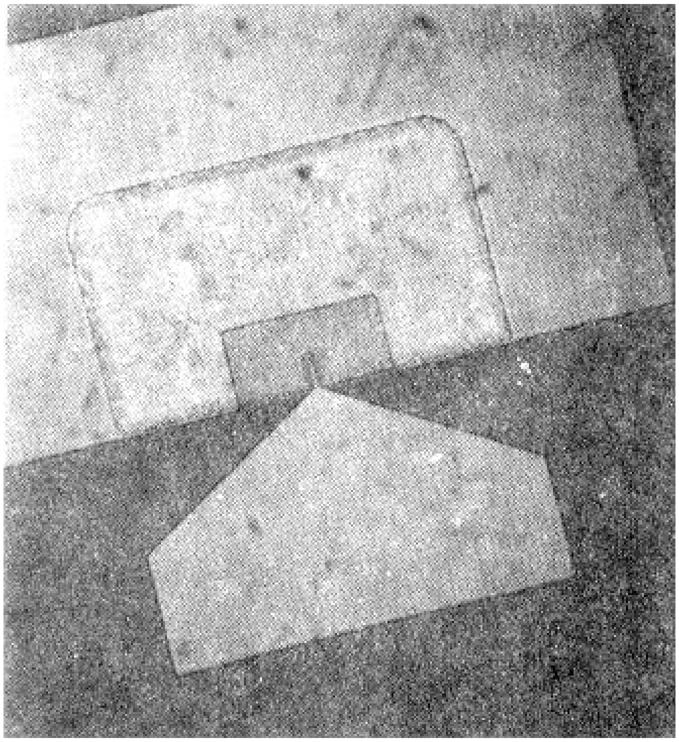

FIGURE 6B PHOTOGRAPH OF MILLIMETER-WAVE BEAM-LEAD DIODE.

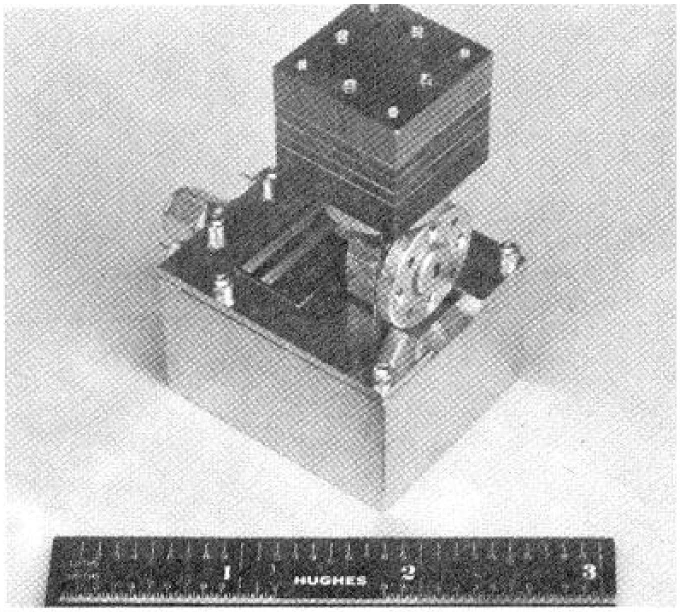

FIGURE 7 94 GHz BALANCED MIXER/IF PREAMPLIFIER WITH RF BAND-PASS FILTER.

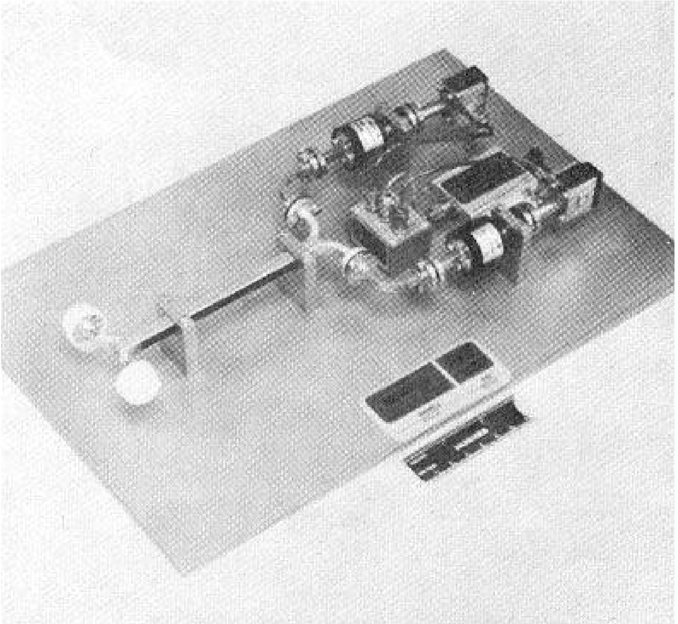

FIGURE 8 BROADBAND (50 GHz TO 75 GHz WAVEGUIDE BALANCED MIXER.

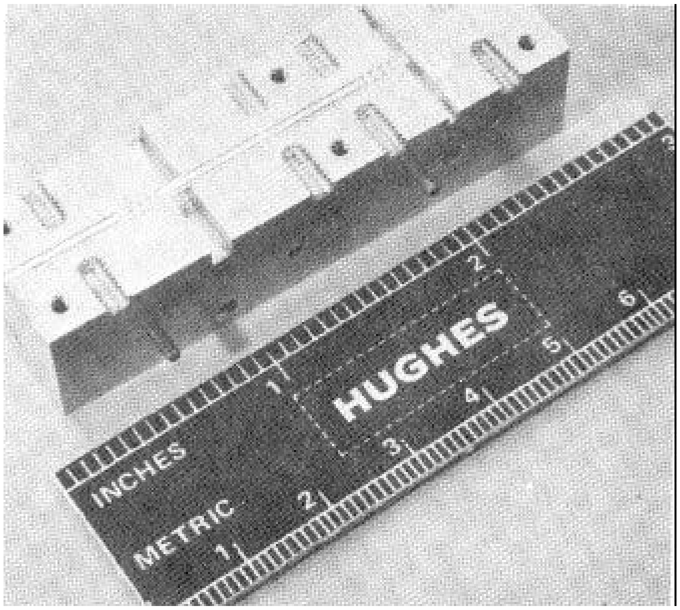

FIGURE 9   94 GHz SUBHARMONICALLY PUMPED MIXER.

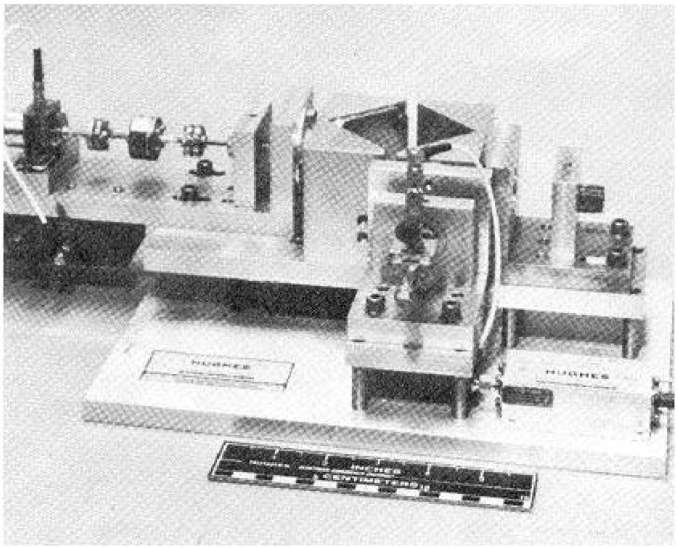

FIGURE 10   217 GHz QUASI-OPTICAL MIXER.

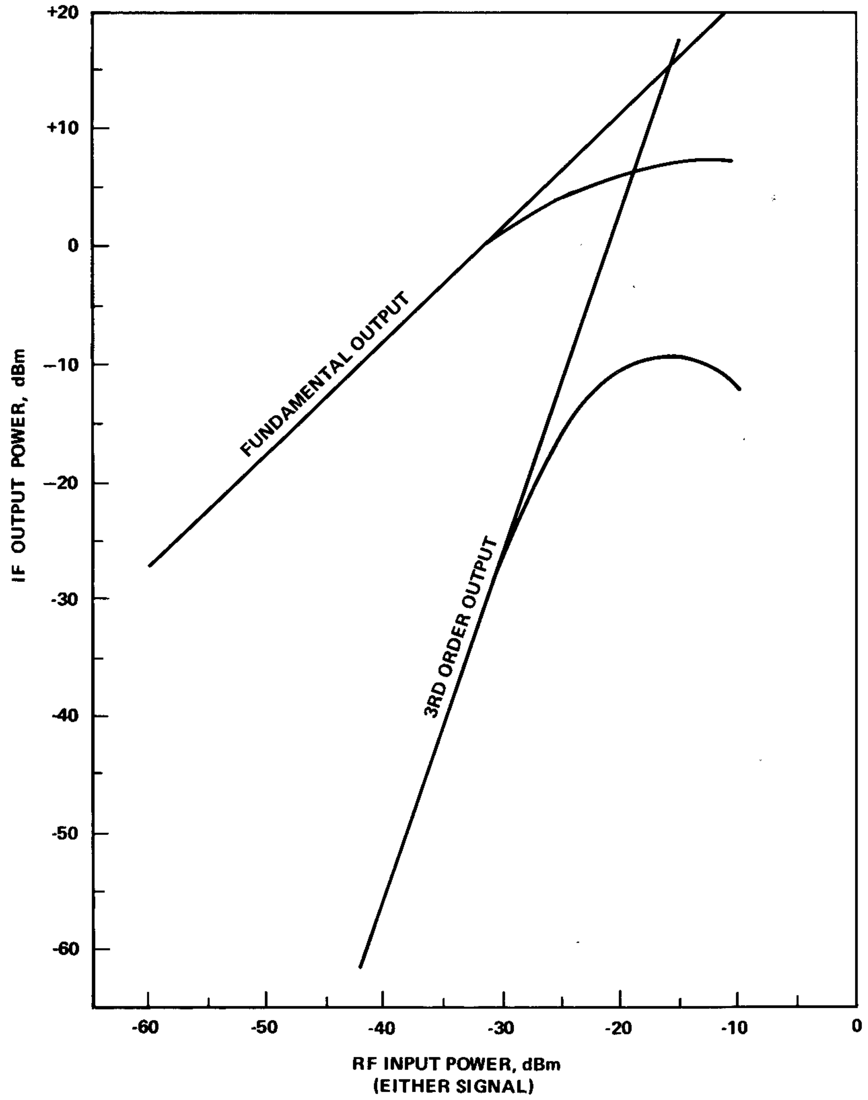

FIGURE 11 INTERCEPT POINT FOR TYPICAL MM-WAVE BALANCED MIXER/IF PREAMPLIFIER.

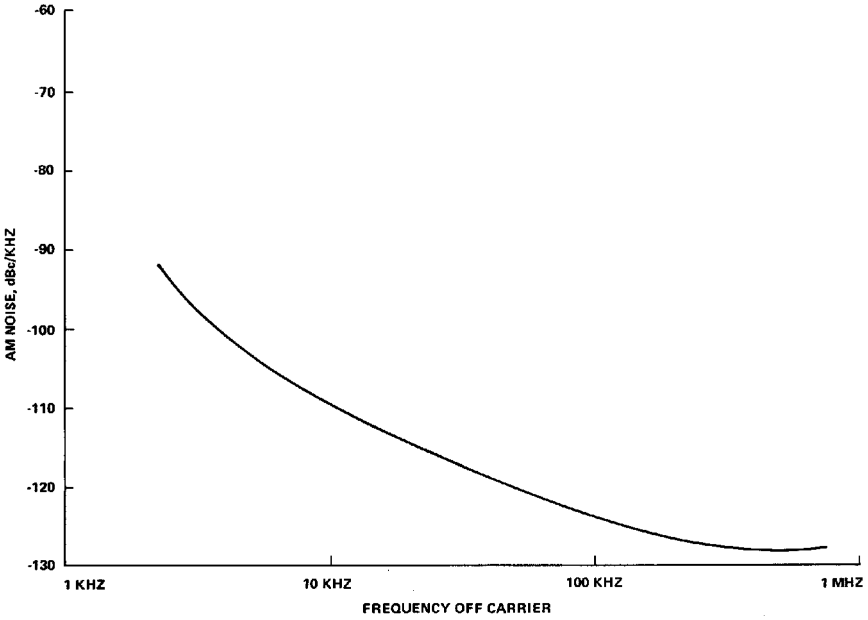

FIGURE 12 SSB AM NOISE OF 94 GHz GUNN OSCILLATOR.

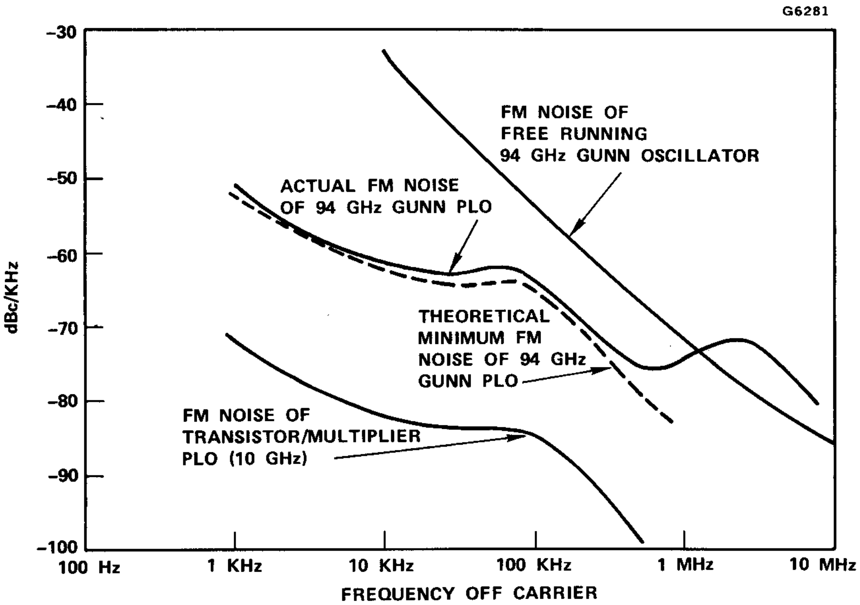

FIGURE 13 SSB FM NOISE OF A 94 GHz PHASE-LOCKED GUNN OSCILLATOR.